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CONSERVATION IN ALFALFA PROCESSING**

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**EFFECT OF FINE CHOPPING, CRUSHING
(SUPERCONDITIONING) AND MACERATION OF ALFALFA
CHOPS ON DRYING EFFICIENCY
DURING ARTIFICIAL DEHYDRATION**

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Summary

While there have been numerous studies indicating that the pre-treatment of alfalfa (macerating or crushing) as it is being mowed will decrease the field drying time, this study did not find a corresponding decrease in high-temperature drying of alfalfa chops treated by chopping, macerating or crushing.

This study found that none of the pre-treatments created a predictable or significant change in the drying time of alfalfa chops dried at 120°C under thin layer conditions. The pre-treatments were repeated three times on three moisture contents of first and second cut alfalfa. The drying curves generally fitted to Page's model of drying, with the exception of five samples that fitted best to the two-term exponential model. The following are the findings of this study:

1. Pretreatment of alfalfa chops by maceration, superconditioning (crushing) or fine chopping before high-temperature drying did not result in significant reduction of drying time.
2. Maceration strips the leaves from the alfalfa chops and broke the stems crosswise, whereas superconditioning split the stems lengthwise. Superconditioning required considerably more additional energy than maceration.
3. The energy and equipment inputs for pretreatment do not seem to justify the small decrease in drying time (and energy).
4. The nutritional analysis showed small changes in the Vitamin A and protein contents of the samples.

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INTRODUCTION

Alfalfa is an important forage crop in Canada. Saskatchewan and Alberta continue to dominate the processed alfalfa in the country, producing over 90% of processed alfalfa. Processed alfalfa production in Canada, consisting of pellets and cubes, was estimated at 570,000 tonnes in the crop year of 2000/2001, down 15% from the 1999/2000 production of 667,000 tonnes (AAFRD, 2001). The past couple of years have been years of consolidation due to changes in the export market and in domestic conditions, notably the volatile natural gas prices. In a 1990 survey of alfalfa dehydrators in Canada, the average costs of producing alfalfa pellets and cubes were \$69.61 per tonne and \$78.61 per tonne, respectively. Of this total cost, fuel and utilities cost were \$15.92 per tonne (23% of cost) and \$12.45 per tonne (16% of cost), respectively for pellets and cubes (AAFRD, 1999). Since eleven years have passed after this survey, the cost components may have changed. Lately, the cost of natural gas has been so volatile that dehydrating plants find it difficult to stay competitive under such conditions. A number plants have closed due to changes in the export market and the high cost of utilities.

Therefore, to remain competitive, alfalfa dehydrators in Western Canada have to be efficient in their processing operations. The steps in processing operation have to be reviewed closely so as to enhance efficiency (cost and production) and, at the same time, maintain the high product quality that Canada is known for. One of the high cost operations in alfalfa processing is drying. Drying has received previous attention from researchers addressing quality concerns. This time, a more pressing issue is how to lower the energy cost of such an operation. With the ever-present possibility of natural gas prices rising drastically in the future, it is imperative that Canadian dehydrators decrease their drying costs in the making of pellets and cubes without compromising their reputation for producing top quality products.

To date, the majority of mechanical pre-treatments have focused on decreasing the drying rate of alfalfa in the field, not in the dehy plant. Macerators and super-conditioners have been designed to break (macerate, crush) the stems of the plant and/or remove or damage the cuticle, decreasing the drying time of the plant by allowing the water to evaporate more freely. This is generally done at ambient temperatures of 20 to

30°C, or on a nice summer day. However, in a processing facility alfalfa chops are generally dried in a rotary drum dryer at temperatures approaching 120°C (250°F) and with an air speed of 7.5 m/s (1500 fpm). This high air speed is used to convey the alfalfa through the dryer, into the hammer mill for grinding (for pelleting operations) and into the pelleter or cuber.

In this project, we looked closely at the effects of treatment of alfalfa chops prior to drying on drying efficiency as well as nutritional quality. The specific objectives of the study were to:

1. determine the drying rates of forage as a factor of four forage pretreatments (maceration, crushing, fine chopping and control (chopping)) at three different initial moisture levels (high, intermediate and low moisture) and time of cutting (first cut and second cut);
2. determine the electrical power consumption per unit of material for the non-control forage treatments.
3. compare the nutritional quality of dried alfalfa subjected to the four pretreatments, three moisture levels and two cutting dates.

MATERIALS AND METHODS

Materials

A total of 72 trials were conducted with fresh-cut alfalfa. For each of the cuts, there were three moisture contents; for each of the three moisture contents, there were four pre-treatments; and for each of the pre-treatments, there were three replicates.

The first-cut alfalfa was swathed the morning of July 4, 2001. The first set of samples was collected immediately after the alfalfa was swathed. The second set of samples was collected approximately 4 hours later. The third set was collected the morning of July 5, 2001. All of the samples were collected from a field 20 km southwest of Saskatoon, Saskatchewan. After the samples were collected, they were immediately cooled and placed into storage at approximately 2°C. These samples remained in storage until the drying equipment was completed. They were dried July 31, August 1, and August 2.

The second cut was harvested on August 17, 2001. The samples were dried on August 21, 22, and 23. As all of the samples were obtained at a high moisture content, it was necessary to mimic field drying for the samples of medium and low moisture content. This is shown in Figure 1. The second cut of alfalfa was cut by hand in the field, instead of by a swather. This was done out of necessity, as the swathing was taking place after the material for these replicates was required.

As there were a large number of samples to be tested over the course of a few days, it was necessary to provide adequate storage to minimize the drying and deterioration of the samples. The first-cut samples were the most crucial to store, as they were harvested almost one month before the equipment was ready to begin the testing.

The samples were stored in a thin layer, in plastic bags, at 2°C in a walk-in cooler. The samples had to be removed periodically to allow the cooling chamber to defrost, at this time the samples were stored at 5°C. The thin-layers and the cool temperature helped prevent heating and slowed down the respiration of the samples. However, some deterioration was inevitable, particularly for the long-term storage of the first cut alfalfa.

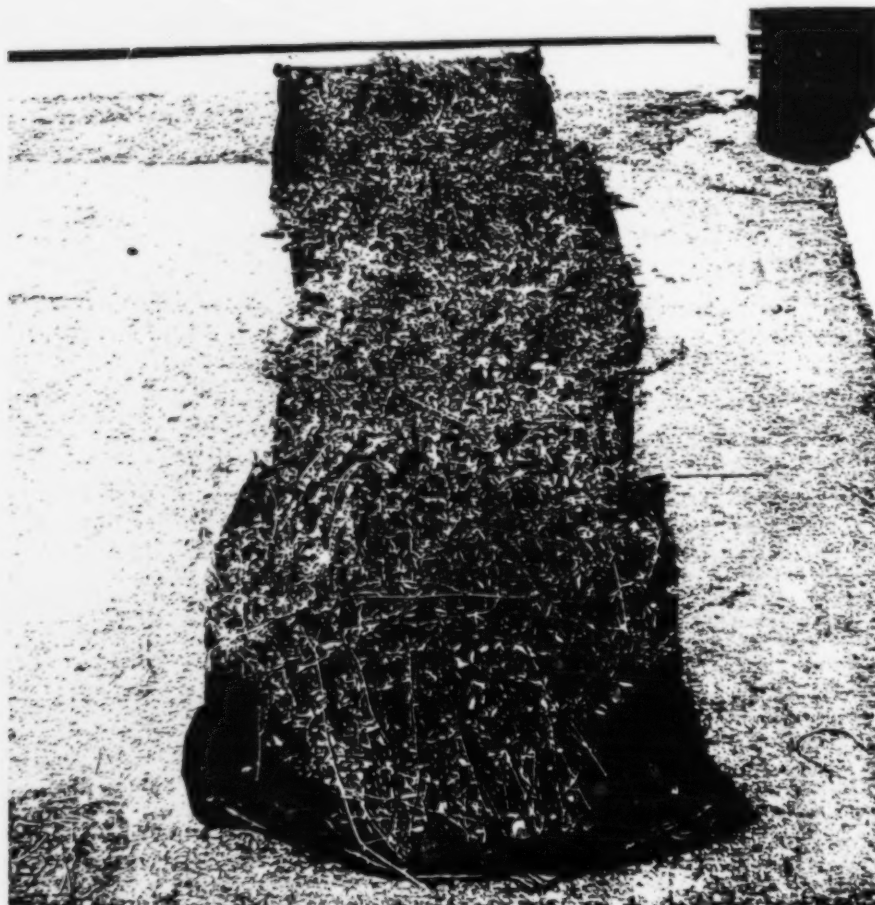


Figure 1. Windrow of alfalfa. This "windrow" was made from alfalfa cut by hand. It was placed in full sun to dry down to 64% and then 55% moisture content (w.b.). This procedure allowed all of the alfalfa to be harvested at the same time and to be stored at the same moisture content.

Chopping

The chopping for these tests was all done by hand. A hedge trimmer was used to cut the alfalfa into pieces roughly 5 to 15 cm long. For the first cut, the chops were also put through a knife mill, without any screens in place (Retsch, Model Falling Number 120, Huddinge, Sweden). This was done in order to ensure a more uniform chop and to blend the samples after storage. However, this was not done for the second cut due to concerns over the condition of the alfalfa chops. The second cut was only chopped using a pair of scissors.

A pair of scissors was also used to create the fine chops. The chops were cut into pieces, 2 to 5 cm long, to be considered fine chops. Figure 2 shows the difference between regular chops and fine chops.



Figure 2. Regular vs. fine alfalfa chops. The regular chops are shown on the left, while the fine chops are shown on the right hand side of the picture.

After the initial chopping, but prior to any other pre-treatments, the sample bags were mixed to ensure consistent moisture content. The samples were then separated into quarters. One quarter of the sample was set aside (chops), one quarter was chopped again (fine chops), one quarter was run through a macerator (macerated chops), and the remainder was run through a superconditioner (crushed chops). Figure 3 shows the difference between regular, macerated and superconditioned chops. The regular chops (top) are in one piece. The superconditioned chops (center) have been split lengthwise. The macerated chops (bottom) have been broken crosswise repeatedly.

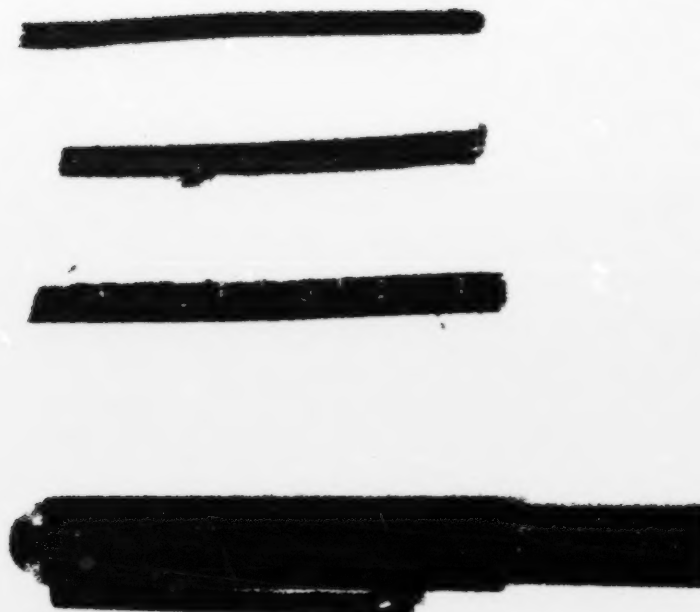


Figure 3. Alfalfa stem sections after pre-treatment: regular chops (top); superconditioned chops (centre); macerated chops (bottom).

Macerating

Maceration was done with a laboratory scale macerator, shown in Figure 4. The macerator was designed in 1992 as an undergraduate design project at the University of Saskatchewan (Hunter, 1992). It consisted of two grooved rollers, spaced 0.3 mm apart, and mounted on bearings on a steel frame. The rollers are shown in Figure 5. A 5 hp (3.75 kW) electric motor drove a variable speed gearbox and chain drive that turned the rollers. The alfalfa chops were fed into the macerating rollers through a hopper on top of the machine.

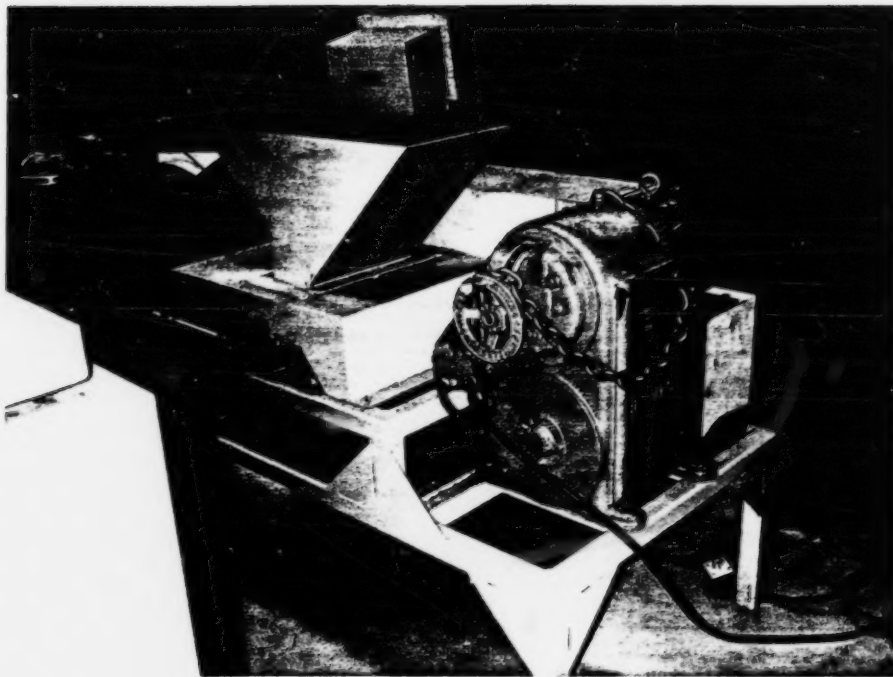


Figure 4. Lab-scale macerator designed at the University of Saskatchewan.



Figure 5. The macerating rollers.

The macerator works by sharply bending the stems of the alfalfa and scraping the cuticle to allow moisture to escape more quickly. The macerated stems are not usually broken. However, the stems can be split if they are oriented parallel to the grooves in the rollers (Winer & Richards, 1996). The electrical power requirements for the macerator were monitored while the material was flowing through. The power monitoring was done to help to estimate the cost of incorporating a conditioner into an alfalfa processing plant.

Crushing

The crushing rollers were a demonstration unit provided by Circle C Equipment, LLC (Hermiston, Oregon) and are shown in Figure 6. They are set up similar to the macerating rollers, however there are a few major differences. The crushing rollers have a diamond-grooved rubber coating on them instead of the straight grooves on the macerating rollers. The diamonds are of different sizes on either roller, shown in Figure 7. The rollers on the superconditioner are pressed together, unlike the rollers on the macerator. Two air bellows push the rollers together, adjusting the amount of force used for crushing. The crushed stems are broken lengthwise to allow the moisture to escape more easily. The electrical power requirements for the superconditioner were also monitored while the material was being crushed.



Figure 6. Superconditioner manufactured by Circle C. Equipment, LLC (Hermiston, Oregon).



Figure 7. Rollers on the superconditioner. The top diamonds are larger and measure 35 mm by 35 mm. The diamonds on the bottom roller are smaller and measure 25 mm by 25 mm.

Thin-Layer Dryer

The thin-layer dryer is shown in Figure 8 and a schematic is shown in Figure 9. The dryer consists of a conditioning chamber attached to a fan that blows the conditioned air through the square ducting. The samples are held on mesh trays that are placed on each of the three tiers of a sample carrier. The sample carrier is mounted on a scale to monitor the moisture loss in a sample. The temperature, air speed, and relative humidity are adjustable and were monitored throughout the tests. The temperature was set at 120°C across the carrier. The relative humidity was not controlled, but it was monitored and did not exceed 7%. The air velocity was set at 1.5 m/s and was monitored throughout testing. This velocity was below conveying velocity and high enough that the speed of the air was not a factor in drying. The system also monitored the sample weight, the sample temperature, the time, and the upstream and downstream air temperatures. The thin-layer dryer underwent some modifications for these tests. The carrier was replaced with a three-tiered carrier that was able to hold large amount of samples; the IR thermocouple was fitted over the carrier tray to monitor the temperature of the sample; and a new LABVIEW 6.0 (National Instruments, Austin, TX) monitoring program was written and tested.

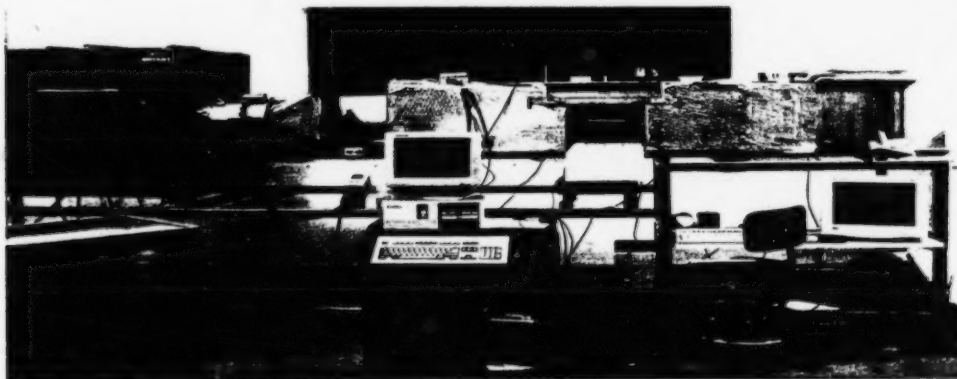


Figure 8. The experimental thin-layer dryer.

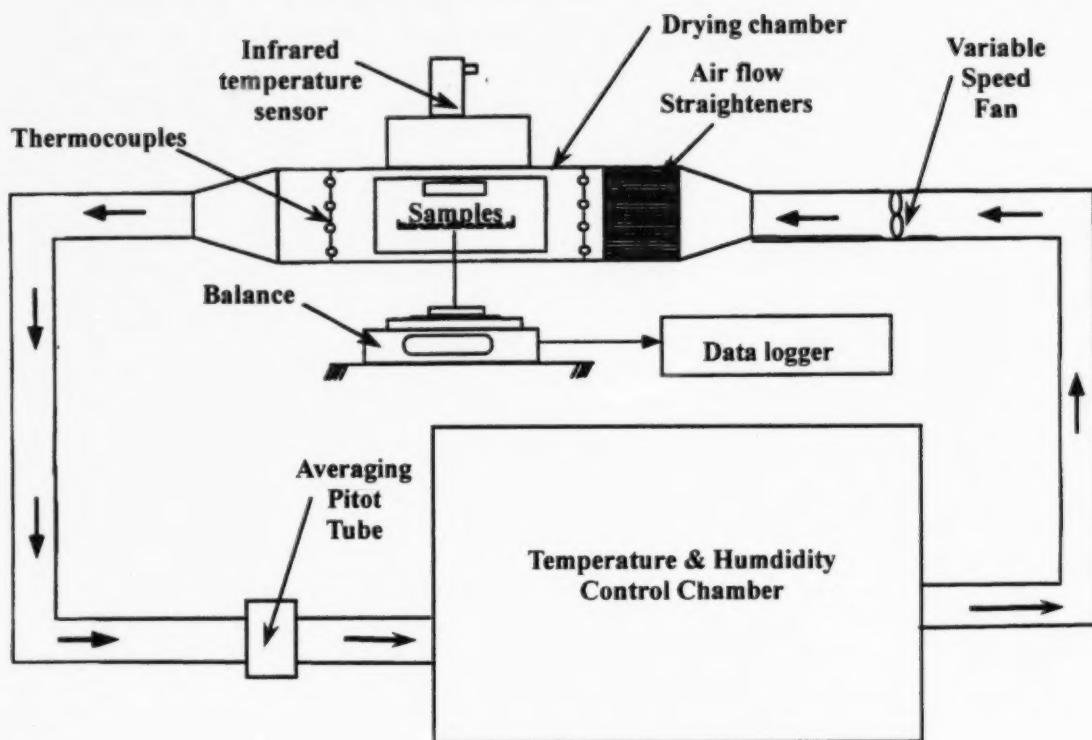


Figure 9. Schematic of experimental thin-layer dryer. It shows the location of the monitoring equipment in the thin-layer dryer.

Moisture Content Determination

Each trial began with the determination of the initial moisture content. This was done with 5 g of the sample being cut into small pieces and dried for one hour at 103°C, in an air oven (Blue 'M', Blue Island, IL). After the initial moisture content was determined, 25 g of the sample was placed in the forage oven to run a parallel moisture test, in accordance with ASAE standard S358.2 (ASAE 1996). The remainder was split into 3 parts. Each part was spread in a thin layer on one of the drying screens for the experimental thin-layer dryer. The screens were then loaded into the carrier and the drying test was done. After the sample was dried, 25 g were reserved for a determination of the final moisture content, while the remainder was sealed in a plastic bag, labeled and stored in a freezer to be sent for subsequent analysis (Figure 10). After drying the data was fitted to drying curves and analyzed.

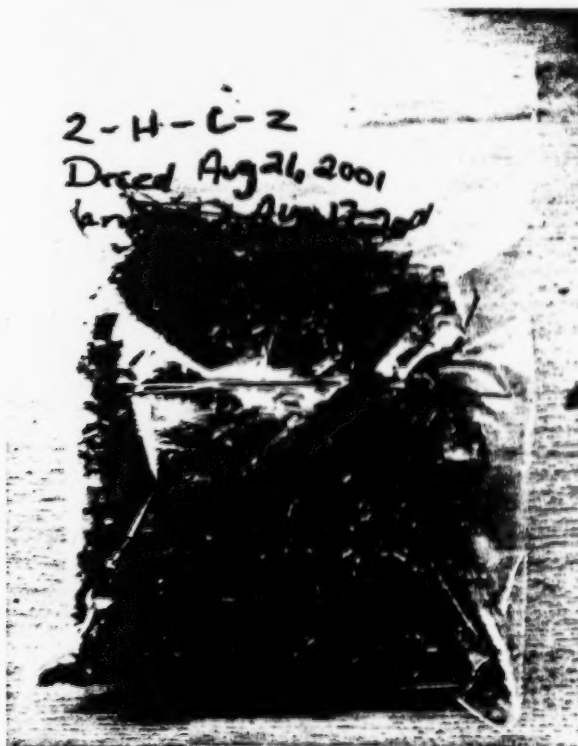


Figure 10. Labeled chops, dried and ready for storage.

The samples were identified by cut (first, second = 1, or 2), initial moisture content (H, M, or L), treatment (C, F, M, or S) and replicate (1, 2, or 3). Thus 2-M-S-3 indicates second cut - medium initial moisture - super-conditioned chops - third replicate. This sample identification was used for both the storage of the samples after they were dried and the filename of the data collected during the drying run.

RESULTS AND DISCUSSIONS

This section has been broken into three parts; Drying Rate, Energy Consumption, and Nutritional Analysis.

Drying Rate

Table 1 shows the initial and final moisture contents of each trial. The final moisture content allowed for the correction of the curves based on moisture that may have been lost in the short time from when the sample was placed into the dryer and the program was started. The initial moisture content allowed us to double-check the final numbers. The final moisture contents for 1-M and 1-L are low due to an error in estimating the initial moisture contents.

Table 1. Initial and final moisture contents for each group of tests.

Sample	Initial moisture content (% w.b.)	Final moisture content (% w.b.)
1-H	72.5%	11.8%
1-M	59.1%	5.6%
1-L	34.9%	5.9%
2-H	71.8%	14.9%
2-M	64.8%	9.7%
2-L	54.6%	14.2%

H- high initial moisture

M- medium initial moisture

L- low initial moisture

It should be noted here that some error was introduced in the drying curves due to the time lapse between placing the sample trays in the carrier and starting the data recording. This is the reason that the samples have a final moisture content ranging from 5.6% to 14.9%. The curves were corrected afterward using the final moisture content of the sample. There were also small changes in the moisture content over the course of the day due to evaporation. The samples were kept in a sealed container, however there was some moisture loss each time the container was opened to gather the next sample. The final moisture content was also used to determine if any material was lost from the tray during the test due to high air speeds. The results showed that there was no loss.

Figure 11 shows a typical set of moisture relation curves. These curves were obtained from the first-cut, low moisture tests. There does not appear to be a noticeable difference in the dry down rates between the four different treatments.

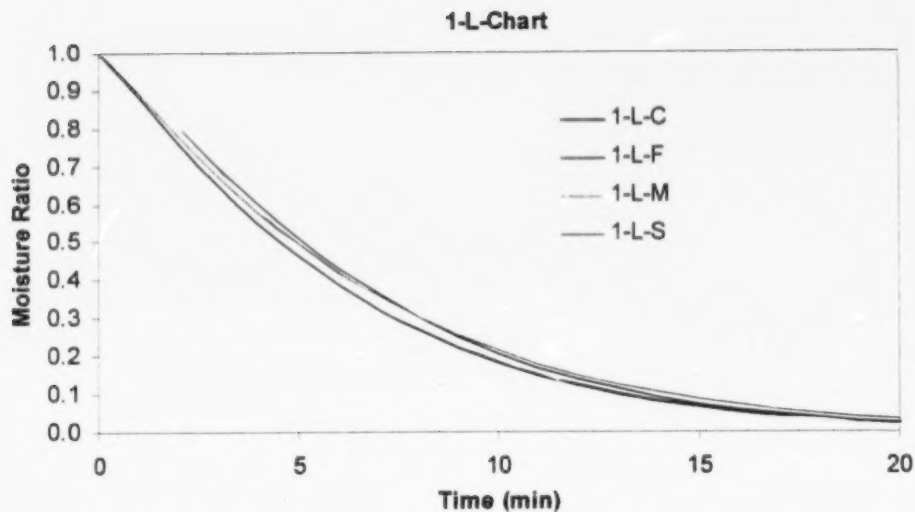


Figure 11. Typical moisture ratio curves. These curves were obtained from the data collected on the first-cut (1), low moisture (L) alfalfa tests. C- regular chops, F- fine chops, M- macerated chops, and S- super-conditioned chops

The data was fitted to various drying curves using MS EXCEL (Microsoft Corp., Redmond, WA). The samples generally fitted best (lowest R^2 value) to Page's equation, with a few exceptions. The first-cut high moisture samples fitted best to the two-term exponential equations, as did the second-cut, high moisture, super-conditioned chops. The best-fit curves are tabulated in Appendix 1. The curves generally fitted very well, with adjusted R^2 values ranging from a minimum of 0.96733 to a maximum of 0.9996 over the 200 to 600 data points that comprise each curve.

For the majority of tests the difference in dry-down time between treatments was not large (Table 2). The only exception was with the first-cut, high-moisture chops, where the fine chops dried down much faster than the other treatments, and the second-cut, medium moisture chops, where the other treatments dried down slightly faster than the untreated chops.

Table 2. Average sample dry-down times.

First Cut		Second Cut	
Sample Group	Average Time to 10% (w.b.) (minutes)	Sample Group	Average Time to 10% (w.b.) (minutes)
1-H-F	36.8	2-H-C	37.2
1-H-M	39.3	2-H-S	38.9
1-H-S	41.3	2-H-F	40.8
1-H-C	41.9	2-H-M	41.9
1-M-M	25.3	2-M-S	27.3
1-M-F	25.9	2-M-M	27.7
1-M-C	26.6	2-M-F	28.0
1-M-S	27.5	2-M-C	33.1
1-L-S	9.0	2-L-S	18.8
1-L-C	9.1	2-L-C	18.9
1-L-M	9.5	2-L-F	21.0
1-L-F	10.0	2-L-M	21.5

$n = 3$

The treatments of the alfalfa chops did not appear to have enough of an impact on the dry down rates of the alfalfa chops to recommend the conditioning of chops prior to entering an alfalfa processing facility.

The seemingly contradictory results of the first-cut, high moisture tests may be explained by the length of time that the samples were stored prior to being dried. The samples were stored for over two weeks while the final preparations for the drying tests were made. While every attempt was made to ensure that the samples were kept fresh and as close to their original condition as possible, some deterioration was inevitable. This may also explain why the first-cut, high-moisture samples did not fit to the Page's equation like the majority of the other samples, but instead fitted to the two-term exponential equation.

Also of interest was the state of the alfalfa chops once they were conditioned. The macerated chops had more of their leaves stripped of and were stickier than the chops that were crushed. It was difficult to tell the difference between the crushed and the unconditioned chops unless the stem was examined.

The equipment used to condition the samples was primarily designed for use on a mower to expedite the drying of alfalfa as it is cut in the field. They were not designed for use with alfalfa chops, as it was assumed that the forage harvester would follow the mower. It is likely that the period where the conditioners would hasten drying the most takes place before and during the chopping process. While the conditioners may shave

crucial minutes or hours off of the drying of alfalfa in the field, the effect appears to be lost under the conditions presented in this report.

Energy Consumption

The energy consumption of the macerator and the superconditioner were monitored during use. The energy input of the thin-layer dryer was not monitored, but it could be estimated based on the amount of moisture removed from the samples. It should be noted that the superconditioner and the macerator were fed by hand, meaning that there was not a consistent flow of material. It should also be noted that while the amount of energy that was used to remove water from the material can be estimated, this does not include the energy that was lost to the surrounding air, or the energy that was used to operate the fan or monitoring equipment.

Due to technical problems, data was collected for only the second cut trials. The macerator tended to use 1000 to 1500 watts over the 'no-load power level). The crusher tended to use almost double that, 2500 to 3000 watts. The power curves for the low moisture chops are shown in Figures 12 and 13. They are representative of the power data collected. Figure 12 is the macerator; Figure 13 is the superconditioner. In both figures there is a spike as feeding begins. In Figure 12 there are two spikes, one for the beginning of each handful of material. Table 3 shows the approximate amount of energy used to treat the samples from the second cut. The values are given in kWh/t. The specific energy consumption for macerating the sample was much lower than that used for superconditioning.

2-L-M Power

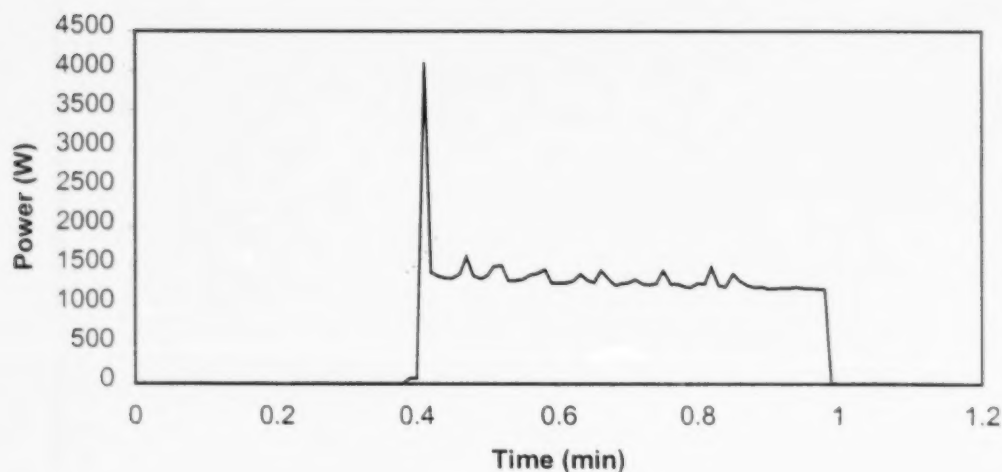


Figure 12 Power curve for the second cut, low moisture, macerated sample.

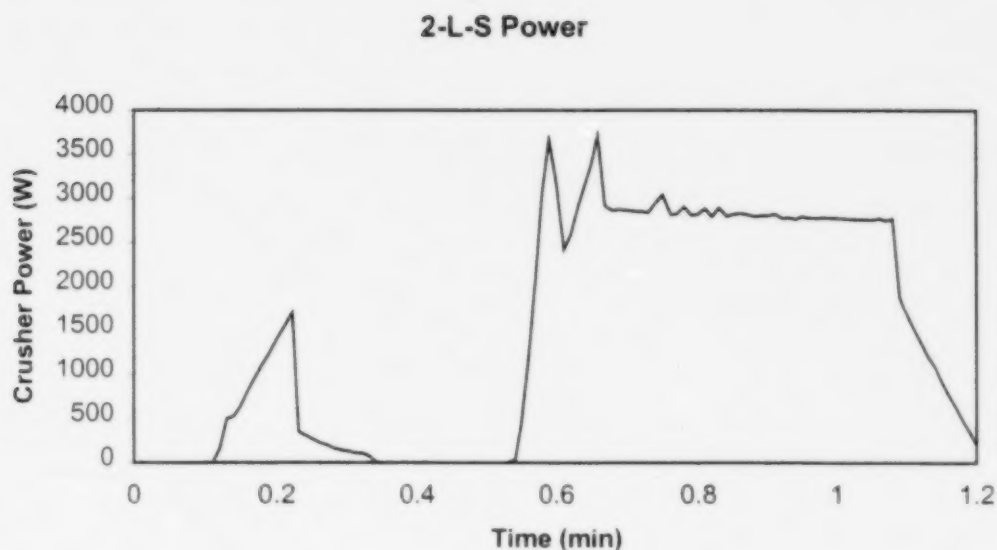


Figure 13 Power curve for the second cut, low moisture, super- conditioned sample.

Table 3. Approximate energy used for the pretreatment of the second cut alfalfa chops.

Sample	Energy consumption (kWh)	Approximate mass (kg)	Specific energy consumption (kWh/t)
2-H-M	0.0174	0.85	20.4
2-H-S	0.1082	0.85	127.3
2-M-M	0.0127	0.75	16.9
2-M-S	0.0420	0.75	56.0
2-L-M	0.0132	0.55	24.1
2-L-S	0.0292	0.55	53.0

Nutritional Analysis

Some of the nutritional factors were also analyzed for the various alfalfa samples. The nutritional analysis was expected to show a decrease (hopefully small) in the protein and Vitamin A contents of the alfalfa. This was likely due simply to the exposure of more protein and Vitamin A to the high temperature air.

Table 3 shows the results of the protein content tests on the various samples. In general, there does not appear to be a significant trend in the protein contents after the various pre-treatments. The percent difference between the highest and lowest values for the first cut is 4.2%, while the percent difference between the treatments of the second cut is 4.8%. The second-cut alfalfa had higher protein contents than the first-cut alfalfa by as much as 2% of dry matter.

The Vitamin A content of the samples was also analyzed (Table 4). The vitamin A content was drastically lower in the first-cut alfalfa than it was in the second-cut, 53,000 IU difference. The untreated alfalfa chops showed the highest Vitamin A content for the first-cut alfalfa and were close to the highest for the second-cut alfalfa. This means that it is likely that any pretreatment will result in a loss of Vitamin A content, though those losses will likely be low.

Since there are places where the pretreatment shows a higher Vitamin A or protein content than the control chops, it suggests that the samples were not large enough to show a statistical trend. The differences in the final moisture contents of the samples may also have affected the protein and Vitamin A contents of the samples.

Table 4. Protein content (% of dry matter) of dried alfalfa samples.

Cut	Moisture level	Control	Macerated	Super-conditioned	Fine chopped
1	H	16.9	16.4	17.1	17.8
	M	19.0	18.0	16.9	18.4
	L	15.8	16.4	16.0	16.0
	Mean	17.2	16.9	16.7	17.4
2	H	17.4	16.7	19.3	18.5
	M	20.1	19.4	18.8	19.0
	L	18.2	18.9	19.7	20.0
	Mean	18.6	18.3	19.3	19.2

Table 5. Vitamin A content (IUPP) of dried alfalfa samples.

Cut	Moisture level	Control	Macerated	Super-conditioned	Fine chopped
1	H	95,000	88,400	90,000	81,700
	M	85,000	70,000	66,700	85,000
	L	56,700	46,700	48,300	55,000
	Mean	78,900	68,367	68,333	73,900
2	H	126,700	116,700	131,700	131,700
	M	136,700	121,700	126,700	110,000
	L	100,000	106,700	106,700	108,700
	Mean	121,133	115,033	121,700	116,800

CONCLUSIONS AND RECOMMENDATIONS

The pretreatment of the alfalfa chops did not predictably reduce the drying time of the alfalfa chops. The high temperature seemed to produce such a high driving force for moisture reduction that other factors became much less significant.

1. Pretreatment of alfalfa chops before high-temperature drying did not have a major impact on the drying time.
2. Maceration strips the leaves from the alfalfa chops and requires considerable additional energy.
3. The energy and equipment inputs for pretreatment do not seem to justify the small decrease in drying time (and energy).
4. The nutritional analysis showed small changes in the Vitamin A and protein contents of the samples

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APPENDIX 1

Page's Model and the Two-Term Exponential equations are Equation 1 and 2 respectively.

Equation 1 Page's Model

$$M.R. = e^{-K \cdot \text{time}^N}$$

Equation 2 Two-Term Exponential Model

$$M.R. = A_0 e^{-K_1 \cdot \text{time}} + A_1 e^{-K_2 \cdot \text{time}}$$

The following table contains the results of the curve fitting operations for the drying tests. The coefficients shown are averaged from the three different repetitions of each treatment. The minimum and maximum Adjusted R^2 values for the equations at each treatment are also shown. It should be noted that there are between 200 and 600 data points for each trial.

Table 6. Coefficients for the best-fit equations and the adjusted R^2 values.

Sample	Best Fit	Coefficients				Adjusted R^2
		A0	A1	K1	K2	
1-H-C	Two-Term Exponential	5.76361	-4.75807	0.05081	0.05079	0.99953
-1	Two-Term Exponential	7.17845	-6.20101	0.09031	0.10008	0.99868
-2	Two-Term Exponential	5.04577	-4.02530	0.02824	0.02374	0.99998
-3	Two-Term Exponential	5.06661	-4.04790	0.03388	0.02854	0.99992
1-H-F	Two-Term Exponential	7.28173	-6.25420	0.02568	0.02186	0.99979
-1	Two-Term Exponential	7.28150	-6.25511	0.02491	0.02102	0.99980
-2	Two-Term Exponential	7.28089	-6.25572	0.02678	0.02285	0.99984
-3	Two-Term Exponential	7.28279	-6.25177	0.02534	0.02170	0.99973
1-H-M	Two-Term Exponential	6.71779	-5.69847	0.03038	0.02647	0.99986
-1	Two-Term Exponential	5.04540	-4.02792	0.03463	0.02991	0.99961
-2	Two-Term Exponential	7.27585	-6.25260	0.02842	0.02437	0.99992
-3	Two-Term Exponential	7.27188	-6.25454	0.02767	0.02447	0.99995
-4	Two-Term Exponential	7.27803	-6.25882	0.03077	0.02713	0.99994
1-H-S	Two-Term Exponential	7.26901	-6.24486	0.02670	0.02333	0.99991
-1	Two-Term Exponential	7.28152	-6.25526	0.02977	0.02605	0.99985
-2	Two-Term Exponential	7.27952	-6.25639	0.02821	0.02470	0.99993
-3	Two-Term Exponential	7.24599	-6.22293	0.02212	0.01923	0.99994

Sample	Best Fit	Coefficients				Adjusted R^2
		K	N			
1-M-C	Page's Model	0.05082	1.19001			0.99885
-1	Page's Model	0.04793	1.24150			0.99783
-2	Page's Model	0.04981	1.18696			0.99917
-3	Page's Model	0.05473	1.14156			0.99955
1-M-F	Page's Model	0.03885	1.26274			0.99883
-1	Page's Model	0.03772	1.28199			0.99873
-2	Page's Model	0.03935	1.25313			0.99887
-3	Page's Model	0.03948	1.25310			0.99889
1-M-M	Page's Model	0.04559	1.22450			0.99841
-1	Page's Model	0.04601	1.20779			0.99909
-2	Page's Model	0.04576	1.24361			0.99768
-3	Page's Model	0.04500	1.22208			0.99846
1-M-S	Page's Model	0.04673	1.18455			0.99689
-1	Page's Model	0.04539	1.18318			0.99926
-2	Page's Model	0.04656	1.21832			0.99834
-3	Page's Model	0.04824	1.15214			0.99308

Sample	Best Fit	Coefficients				Adjusted R ²
		K	N			
1-L-C	Page's Model	0.12307	1.13998			0.99978
-1	Page's Model	0.11101	1.17016			0.99967
-2	Page's Model	0.10974	1.19024			0.99994
-3	Page's Model	0.14845	1.05956			0.99971
1-L-F	Page's Model	0.09166	1.23565			0.99973
-1	Page's Model	0.07065	1.22971			0.99963
-2	Page's Model	0.10808	1.27127			0.99969
-3	Page's Model	0.09624	1.20596			0.99986
1-L-M	Page's Model	0.09228	1.25829			0.99959
-1	Page's Model					No Data
-2	Page's Model	0.09228	1.25829			0.99959
-3	Page's Model					No Data
1-L-S	Page's Model	0.09054	1.26819			0.99791
-1	Two-Term Exponential	0.06944	1.39500			0.99917
-2	Page's Model					No Data
-3	Page's Model	0.11165	1.14138			0.99664

Sample	Best Fit	Coefficients				Adjusted R ²
		K	N			
2-H-C	Page's Model	0.03806	1.14360			0.97525
-1	Page's Model	0.03807	1.14666			0.92841
-2	Page's Model	0.03725	1.13153			0.99972
-3	Page's Model	0.03886	1.15261			0.99762
2-H-F	Page's Model	0.02361	1.27513			0.99280
-1	Page's Model	0.02602	1.24614			0.99896
-2	Page's Model	0.02409	1.27208			0.99857
-3	Page's Model	0.02071	1.30716			0.98089
2-H-M	Page's Model	0.03182	1.19655			0.99907
-1	Page's Model	0.02996	1.21466			0.99893
-2	Page's Model	0.03401	1.18313			0.99899
-3	Page's Model	0.03151	1.19186			0.99930
		A0	A1	K1	K2	
2-H-S	Two-Term Exponential	7.29981	-6.33483	0.10004	0.11084	0.98304
-1	Page's Model					
-2	Two-Term Exponential	7.28594	-6.34789	0.09847	0.11013	0.96733
-3	Two-Term Exponential	7.31368	-6.32178	0.10160	0.11155	0.99874

Sample	Best Fit	Coefficients				Adjusted R ²
		K	N			
2-M-C	Page's Model	0.03728	1.22753			0.99942
-1	Page's Model	0.03738	1.23060			0.99937
-2	Page's Model	0.03893	1.21415			0.99947
-3	Page's Model	0.03554	1.23785			0.99942
2-M-F	Page's Model	0.03135	1.31906			0.99881
-1	Page's Model	0.03199	1.33070			0.99858
-2	Page's Model	0.03076	1.31627			0.99895
-3	Page's Model	0.03131	1.31019			0.99888
2-M-M	Page's Model	0.03739	1.27988			0.99884
-1	Page's Model	0.04010	1.25817			0.99907
-2	Page's Model	0.04284	1.22686			0.99896
-3	Page's Model	0.02922	1.35460			0.99850
2-M-S	Page's Model	0.04526	1.22056			0.99863
-1	Page's Model	0.05035	1.19301			0.99889
-2	Page's Model	0.04151	1.22571			0.99879
-3	Page's Model	0.04391	1.24296			0.99820

Sample	Best Fit	Coefficients				Adjusted R ²
		K	N			
2-L-C	Page's Model	0.05906	1.23990			0.99986
-1	Page's Model	0.05913	1.25243			0.99989
-2	Page's Model	0.06076	1.23924			0.99986
-3	Page's Model	0.05728	1.22801			0.99983
2-L-F	Page's Model	0.04923	1.26700			0.99969
-1	Page's Model	0.05402	1.29531			0.99977
-2	Page's Model	0.04482	1.25694			0.99948
-3	Page's Model	0.04885	1.24875			0.99983
2-L-M	Page's Model	0.05489	1.21236			0.99959
-1	Page's Model	0.05701	1.24325			0.99951
-2	Page's Model	0.05231	1.19762			0.99937
-3	Page's Model	0.05535	1.19622			0.99989
2-L-S	Page's Model	0.04981	1.21783			0.99964
-1	Page's Model	0.05135	1.21785			0.99978
-2	Page's Model	0.05032	1.23063			0.99975

APPENDIX 2

Drying Times

Table 7. Drying times for tests.

a) High moisture

First Cut

Sample	Dry down time to 10% w.b. (min)
1-H-F-1	36.36
1-H-F-2	35.21
1-H-F-3	38.79
1-H-F-Average	36.65
1-H-M-1	43.13
1-H-M-2	33.60
1-H-M-3	43.01
1-H-M-4	37.39
1-H-M-Average	38.59
1-H-S-1	36.78
1-H-S-2	38.67
1-H-S-3	48.43
1-H-S-Average	41.42
1-H-C-1	42.04
1-H-C-2	36.47
1-H-C-3	47.30
1-H-C-Average	41.52

Second Cut

Sample	Dry down time to 10% w.b. (min)
2-H-F-1	41.90
2-H-F-2	40.47
2-H-F-3	39.98
2-H-F-Average	40.65
2-H-M-1	40.82
2-H-M-2	41.03
2-H-M-3	43.90
2-H-M-Average	41.77
2-H-S-1	47.49
2-H-S-2	40.93
2-H-S-3	36.94
2-H-S-Average	41.46
2-H-C-1	44.15
2-H-C-2	27.93
2-H-C-3	39.38
2-H-C-Average	34.64

b) Intermediate moisture

First Cut

Sample	Time to 10% w.b. (min)
1-M-F-1	24.91
1-M-F-2	26.45
1-M-F-3	26.43
1-M-F-Average	25.90
1-M-M-1	26.29
1-M-M-2	23.83
1-M-M-3	25.84
1-M-M-Average	25.27
1-M-S-1	28.99
1-M-S-2	24.98
1-M-S-3	28.44
1-M-S-Average	27.30
1-M-C-1	24.68
1-M-C-2	26.32
1-M-C-3	28.67
1-M-C-Average	26.29

Second Cut

Sample	Time to 10% w.b. (min)
2-M-F-1	26.58
2-M-F-2	28.73
2-M-F-3	28.64
2-M-F-Average	27.98
2-M-M-1	27.38
2-M-M-2	27.93
2-M-M-3	27.67
2-M-M-Average	27.67
2-M-S-1	26.99
2-M-S-2	28.91
2-M-S-3	25.98
2-M-S-Average	27.26
2-M-C-1	32.75
2-M-C-2	33.38
2-M-C-3	33.17
2-M-C-Average	33.11

c) Low moisture
First Cut

Sample	Time to 10% w.b. (min)
1-L-F-1	12.62
1-L-F-2	7.93
1-L-F-3	9.50
1-L-F-Average	9.93
1-L-M-1	11.1
1-L-M-2	9.29
1-L-M-3	9.68
1-L-M-Average	9.99
1-L-S-1	8.93
1-L-S-2	Data Unavailable
1-L-S-3	9.00
1-L-S-Average	8.96
1-L-C-1	9.38
1-L-C-2	9.17
1-L-C-3	8.73
1-L-C-Average	9.11

Second Cut

Sample	Time to 10% w.b. (min)
2-L-F-1	17.84
2-L-F-2	23.23
2-L-F-3	22.03
2-L-F-Average	20.72
2-L-M-1	18.81
2-L-M-2	22.53
2-L-M-3	23.21
2-L-M-Average	21.26
2-L-S-1	10.33
2-L-S-2	22.12
2-L-S-3	24.07
2-L-S-Average	14.33
2-L-C-1	18.15
2-L-C-2	18.65
2-L-C-3	20.01
2-L-C-Average	18.85

APPENDIX 3

Energy Used To Evaporate Water

These values do not include the efficiency of the dryer or the amount of energy that was lost to the surroundings. They also do not take the air recycling into account.

Table 8. Approximate values for the amount of energy used to remove water from the samples.

Sample	Initial Weight (g)	Initial Moisture Content (% w.b.)	Final Weight (g) - 10% w.b.	Moisture Removed (g)	Energy Consumed (kJ)
1-H-F-1	208.74	70.6%	67.55	141.19	328.68
1-H-F-2	205.74	69.8%	68.41	137.33	319.69
1-H-F-3	207.17	70.1%	68.16	139.01	323.61
1-H-F-Average	207.22	70.1%	68.05	139.17	323.99
1-H-M-1	217.39	71.9%	67.24	150.15	349.54
1-H-M-2	205.89	69.0%	70.12	135.77	316.07
1-H-M-3	219.48	71.7%	68.28	151.20	352.00
1-H-M-4	202.37	70.5%	65.67	136.70	318.24
1-H-M-Average	209.25	70.4%	68.08	141.23	328.77
1-H-S-1	211.77	70.0%	69.81	141.96	330.47
1-H-S-2	222.69	70.2%	73.02	149.67	348.42
1-H-S-3	231.66	72.2%	70.97	160.69	374.09
1-H-S-Average	222.04	70.8%	71.34	150.77	350.99
1-H-C-1	215.92	71.1%	68.63	147.29	342.89
1-H-C-2	199.92	69.6%	66.83	133.09	309.83
1-H-C-3	230.49	73.0%	68.35	162.14	377.45
1-H-C-Average	215.44	71.3%	68.13	147.51	343.39
Average	213.79	70.7%	68.79	145.09	337.77

1-M-M-1	176.02	59.4%	78.68	97.34	226.60
1-M-M-2	173.88	57.3%	81.66	92.22	214.69
1-M-M-3	173.54	57.6%	80.92	92.62	215.62
1-M-M-Average	174.48	58.1%	80.43	94.06	218.97
1-M-F-1	178.47	57.2%	84.04	94.43	219.82
1-M-F-2	175.79	57.6%	82.07	93.72	218.18
1-M-F-3	176.96	57.9%	81.90	95.06	221.30
1-M-F-Average	177.07	57.6%	82.67	94.40	219.77
1-M-C-1	168.94	58.7%	76.81	92.13	214.48
1-M-C-2	170.50	57.1%	80.45	90.05	209.63
1-M-C-3	172.63	59.5%	77.00	95.63	222.64
1-M-C-Average	170.69	58.4%	78.09	92.61	215.58
1-M-S-1	175.49	59.2%	78.69	96.80	225.36
1-M-S-2	176.26	57.4%	82.67	93.59	217.87
1-M-S-3	181.54	58.8%	82.28	99.26	231.08
1-M-S-Average	177.76	58.5%	81.22	96.55	224.77
Average	175.00	58.1%	80.60	94.41	219.77

Sample	Initial Weight (g)	Initial Moisture Content (% w.b.)	Final Weight (g) - 10% w.b.	Moisture Removed (g)	Energy Consumed (kJ)
1-L-S-1	55.07	31.1%	41.75	13.32	31.01
1-L-S-2					
1-L-S-3	48.19	29.7%	37.27	10.92	25.43
1-L-S-Average	51.63	30.4%	39.53	12.12	28.22
1-L-C-1	40.59	32.5%	30.14	10.45	24.34
1-L-C-2	38.77	32.9%	28.62	10.15	23.63
1-L-C-3	38.78	31.9%	29.05	9.73	22.65
1-L-C-Average	39.38	32.4%	29.27	10.11	23.54
1-L-M-1					
1-L-M-2	117.51	32.6%	87.17	30.34	70.63
1-L-M-3	120.31	37.1%	83.18	37.13	86.44
1-L-M-Average	118.91	34.9%	85.21	33.73	78.53
1-L-F-1	51.39	34.1%	37.24	14.15	32.95
1-L-F-2	38.56	32.6%	28.60	9.96	23.19
1-L-F-3	46.74	31.4%	35.29	11.45	26.66
1-L-F-Average	45.56	32.7%	33.74	11.85	27.60
Average	59.59	32.6%	44.19	15.76	36.69

2-H-C-1	198.66	72.2%	60.85	137.81	320.83
2-H-C-2	198.23	63.4%	79.81	118.42	275.67
2-H-C-3	198.26	70.6%	64.10	134.16	312.33
2-H-C-Average	198.38	68.7%	68.26	130.13	302.94
2-H-S-1	198.55	73.2%	58.58	139.97	325.84
2-H-S-2	197.57	12.7%	189.83	7.74	18.02
2-H-S-3	197.06	70.3%	64.27	132.79	309.12
2-H-S-Average	197.73	52.1%	104.27	93.50	217.66
2-H-F-1	197.64	73.3%	58.15	139.49	324.73
2-H-F-2	200.12	72.2%	61.30	138.82	323.17
2-H-F-3	198.55	18.4%	178.14	20.41	47.51
2-H-F-Average	198.77	54.6%	99.24	99.57	231.80
2-H-M-1	198.01	71.7%	61.74	136.27	317.24
2-H-M-2	197.97	71.2%	62.75	135.22	314.80
2-H-M-3	198.13	71.1%	62.98	135.15	314.62
2-H-M-Average	198.04	71.3%	62.49	135.55	315.55
Average	198.23	61.7%	83.56	114.69	266.99

Sample	Initial Weight (g)	Initial Moisture Content (% w.b.)	Final Weight (g) - 10% w.b.	Moisture Removed (g)	Energy Consumed (kJ)
2-M-S-1	150.14	64.4%	58.83	91.31	212.58
2-M-S-2	157.73	63.4%	63.42	94.31	219.55
2-M-S-3	157.19	62.4%	64.96	92.23	214.70
2-M-S-Average	155.02	63.4%	62.38	92.62	215.61
2-M-M-1	156.86	65.2%	59.96	96.90	225.57
2-M-M-2	155.81	64.1%	61.56	94.25	219.41
2-M-M-3	156.65	64.3%	61.55	95.10	221.39
2-M-M-Average	156.44	64.5%	61.03	95.42	222.13
2-M-F-1	157.35	62.9%	64.16	93.19	216.94
2-M-F-2	157.89	63.4%	63.50	94.39	219.73
2-M-F-3	158.17	63.4%	63.66	94.51	220.01
2-M-F-Average	157.80	63.3%	63.78	94.03	218.90
2-M-C-1	168.17	66.0%	62.97	105.20	244.91
2-M-C-2	168.58	65.9%	63.29	105.29	245.11
2-M-C-3	168.07	65.3%	64.07	104.00	242.11
2-M-C-Average	168.27	65.7%	63.44	104.83	244.04
Average	159.38	64.2%	62.70	96.72	225.17

2-L-S-1	138.09	54.1%	69.66	68.43	159.30
2-L-S-2	137.81	54.0%	69.73	68.08	158.50
2-L-S-3	163.02	52.2%	85.77	77.25	179.83
2-L-S-Average	146.31	53.4%	74.94	71.25	165.88
2-L-C-1	113.23	56.8%	53.81	59.42	138.33
2-L-C-2	112.90	54.8%	56.07	56.83	132.29
2-L-C-3	115.21	55.6%	56.31	58.90	137.12
2-L-C-Average	113.78	55.7%	55.40	58.38	135.91
2-L-F-1	112.51	54.2%	56.72	55.79	129.87
2-L-F-2	142.18	56.1%	68.60	73.58	171.30
2-L-F-3	137.62	54.4%	69.09	68.53	159.53
2-L-F-Average	130.77	54.9%	64.89	65.97	153.57
2-L-M-1	136.12	53.3%	69.91	66.21	154.12
2-L-M-2	162.62	52.6%	84.79	77.83	181.18
2-L-M-3	138.12	55.1%	68.28	69.84	162.58
2-L-M-Average	145.62	53.7%	74.24	71.29	165.96
Average	134.12	54.4%	67.23	66.72	155.33

